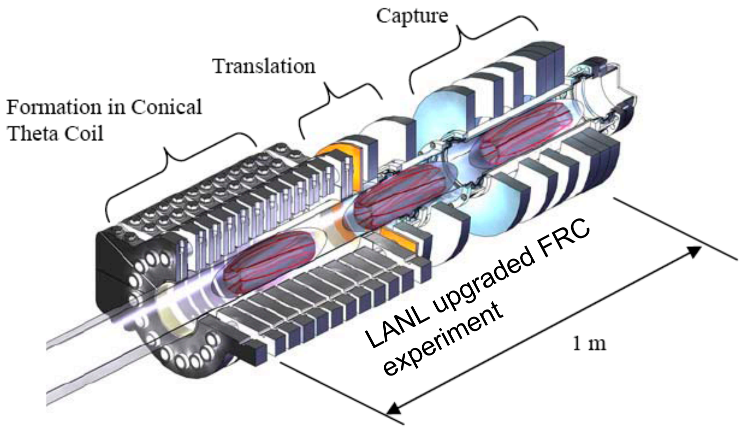
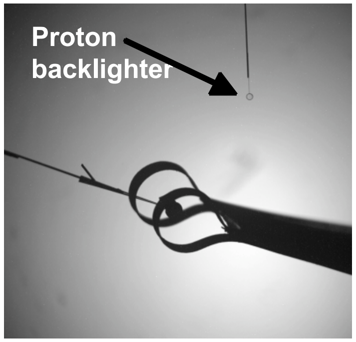
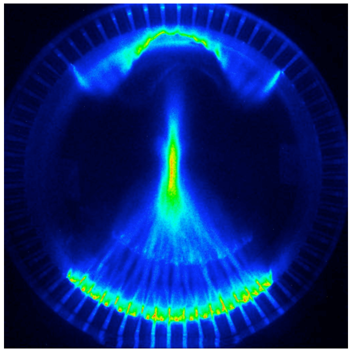


Flux compression on OMEGA



HyperV plasma jet studies



Magnetized HEDLP and Magneto-Inertial Fusion (MIF)

Scott C. Hsu (LANL)

on behalf of the magnetized HEDLP & MIF community

HEDLP Lead Program Manager: Francis Thio

DOE-OFES FY10 Budget Planning Meeting

Gaithersburg, MD

March 12, 2008

Los Alamos NATIONAL LABORATORY EST.1943
Operated by Los Alamos National Security, LLC for NNSA

LA-UR-08-1523

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

Outline

- Program rationale, overview, goals
- Project highlights
- Budgets

Overarching question for magnetized HEDLP and MIF:

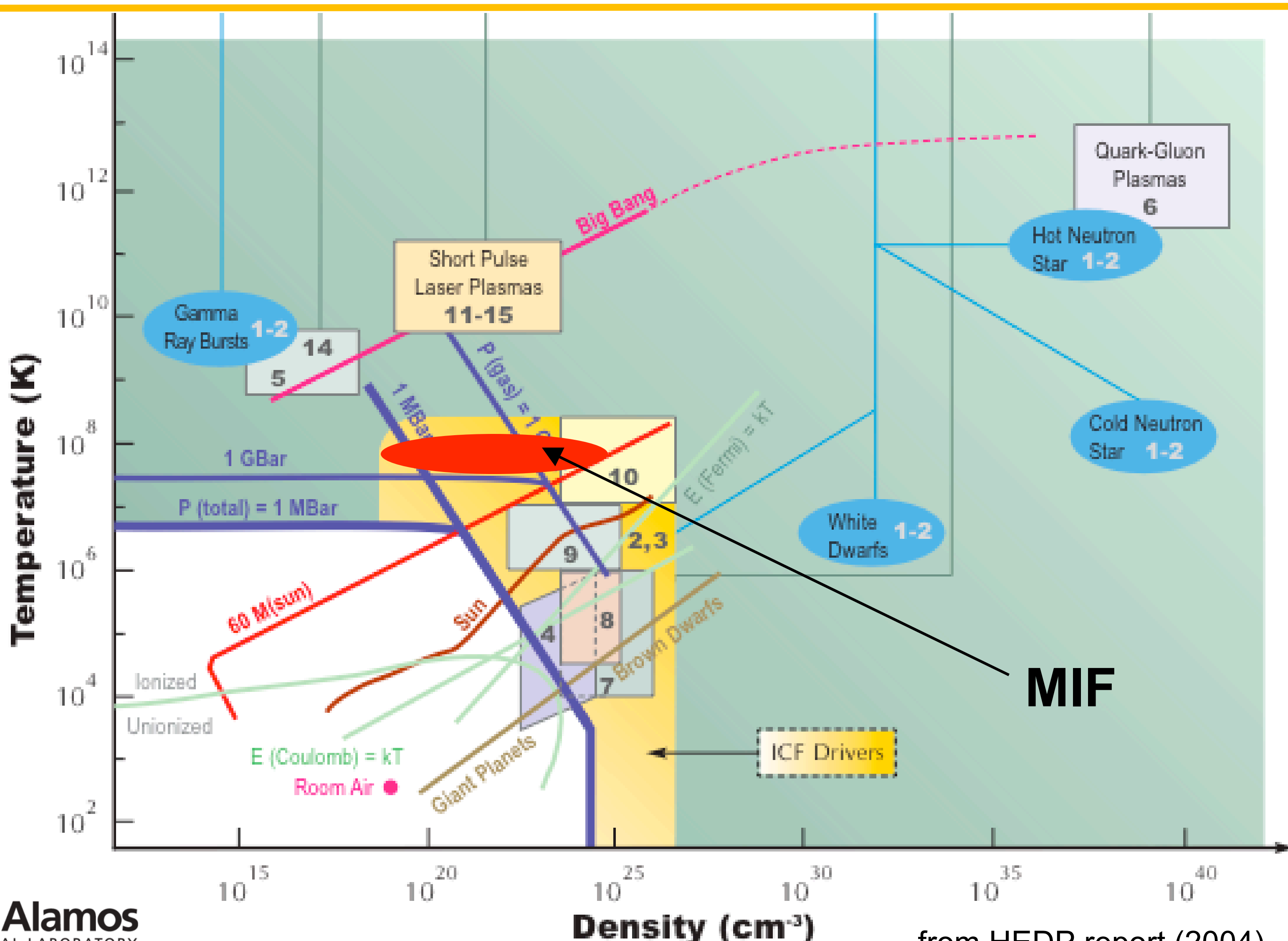
Can an inertially confined plasma with ultra-high magnetic field (≥ 500 T) be assembled to reach fusion conditions?

Program rationale: Tackle tough problems in support of inertial fusion energy science

Magnetic field in target reduces thermal transport → enables lower implosion velocity →

- Offers wider parameter space ("knobs") for optimizing (gain × efficiency) product
- Frees us from cryogenic ICF targets, which are tough to fabricate within required tolerances
- Cheaper per unit driver energy (*e.g.*, pulsed power drivers)
- Relaxes compression ratio requirement and associated instabilities due to reduced $(\rho r)_{ign}$

MIF occurs in the HEDLP regime (> 1 Mbar)



from HEDP report (2004)

MIF and magnetized HEDLP* are mutually enabling

"The behavior of dense plasmas in ultrahigh magnetic fields, a relatively unexplored and intellectually rich regime of plasma physics, has potential applications to energy as well as astrophysics and materials science."

-Report of the Interagency Task Force on HEDP (2007)

MIF ⟷ **magnetized HEDLP**

*Community white paper (4/07) on MHEDLP & MIF available at http://fusionenergy.lanl.gov/mhedlp-wp.pdf

Program overview

magnetized HEDLP science

laboratory astrophysics

theory/modeling

diagnostic innovation

MIF

high gain MIF
(magnetized ICF)

How to create strong B-fields in ICF hot spot?

solid-liner MIF
(liners, targets, integrated experiment)

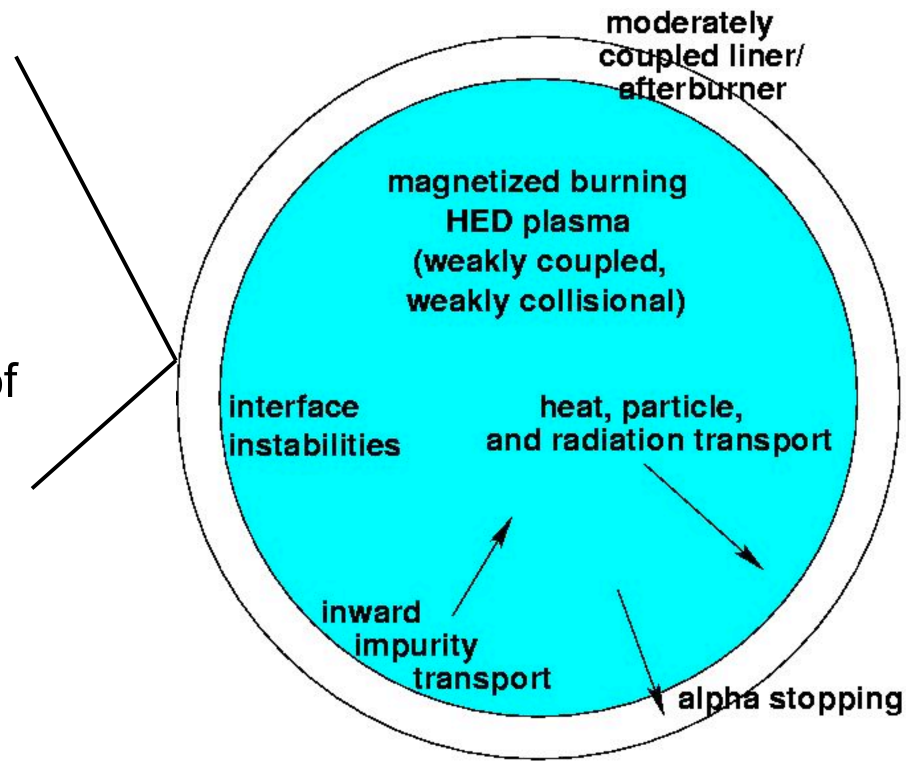
What limits T, n, τ_{dwell} of imploded MHED plasma?

plasma-liner MIF
(PJMIF, staged Z pinch, …)

Can we solve standoff problem and increase MIF gain?

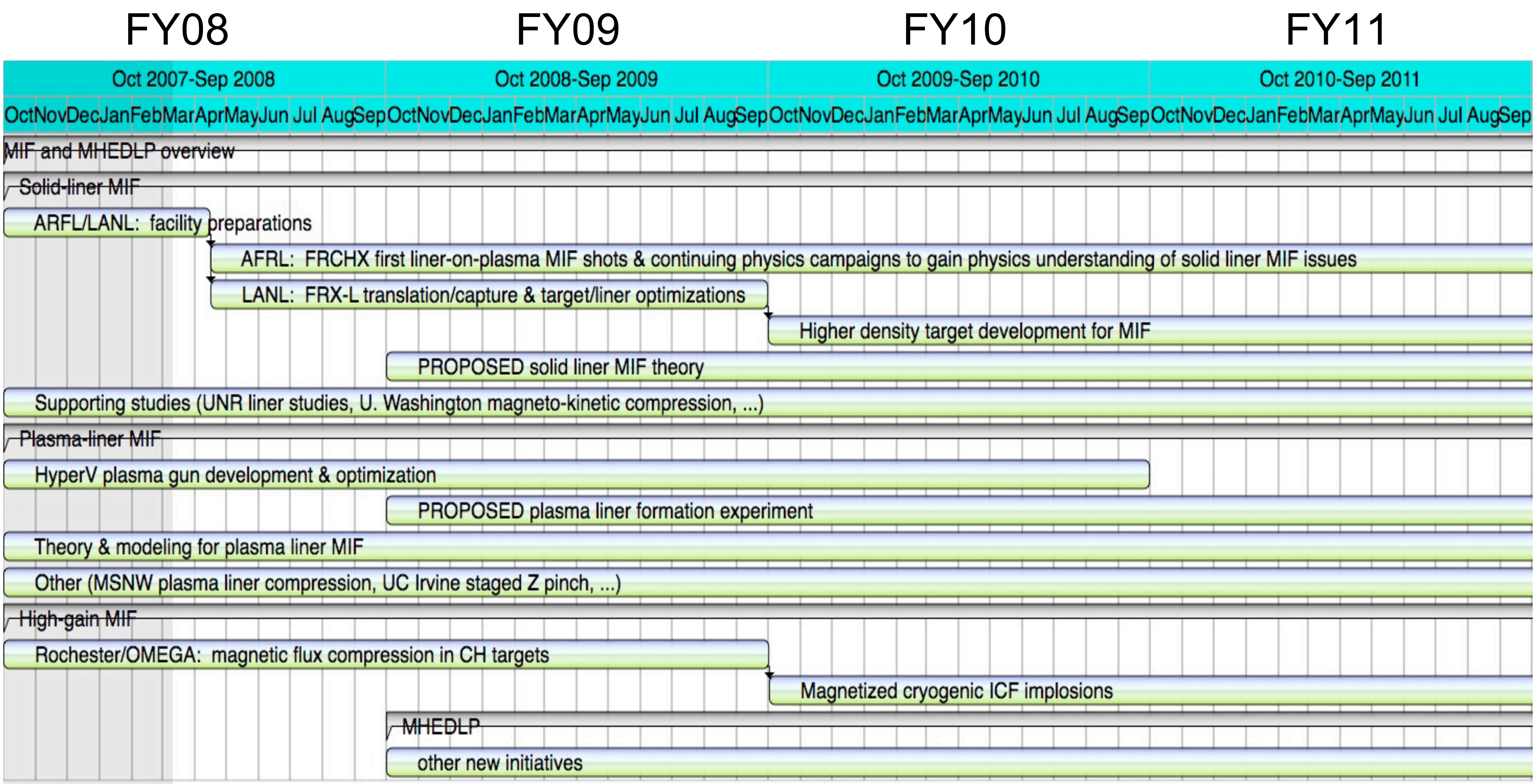
Short term goal (FY09-12) is to demonstrate the physics bases for low/intermediate & high gain MIF

- *Solid liner MIF*: build fundamental database on magnetized HED plasma transport and implosion dynamics
- *Plasma liner MIF*: formation of converging plasma liner capable of approaching 1 Mbar stagnation pressures
- *High gain MIF*: magnetization (>2000T) of ICF hot spot in cryogenic implosions

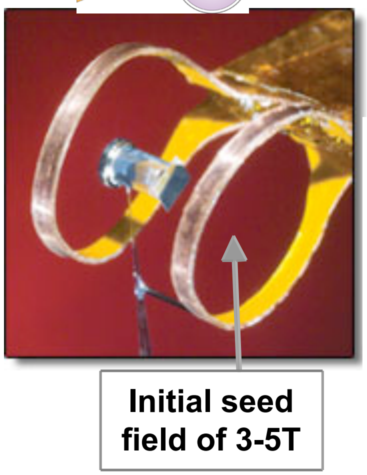


MHEDLP physics issues must be addressed to enable predictive capability for MIF performance

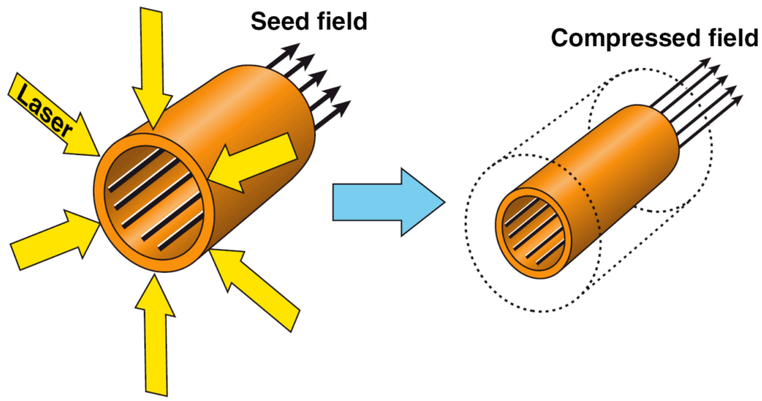
Summary of projects/timelines (FY08-FY11) within MIF program

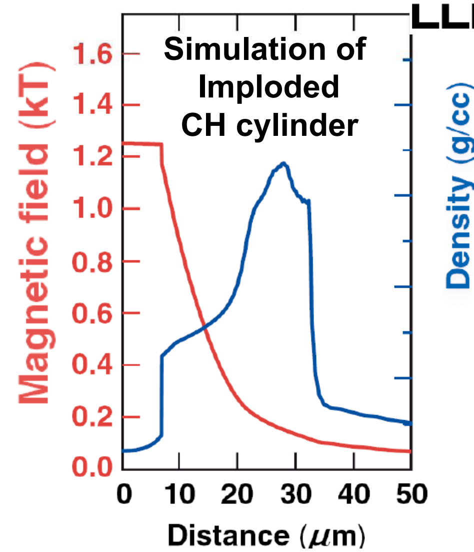


Laser-driven magnetic field compression used to magnetize ICF target hot spot; ~1300T achieved

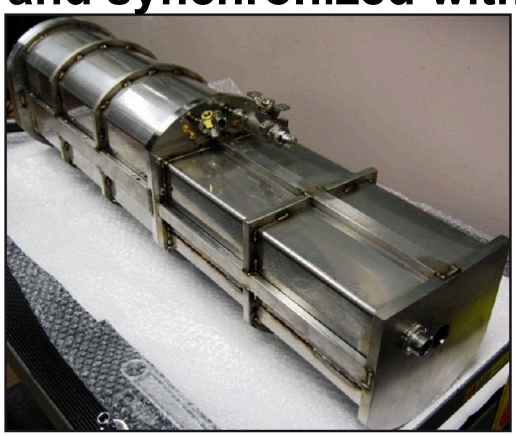


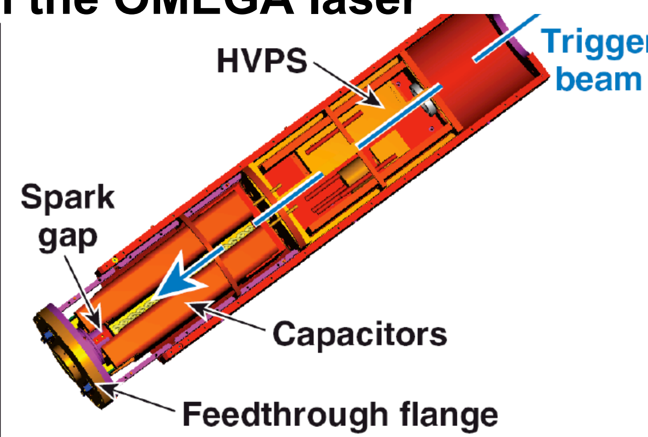
A magnetized ICF implosion yields higher hot-spot temperatures

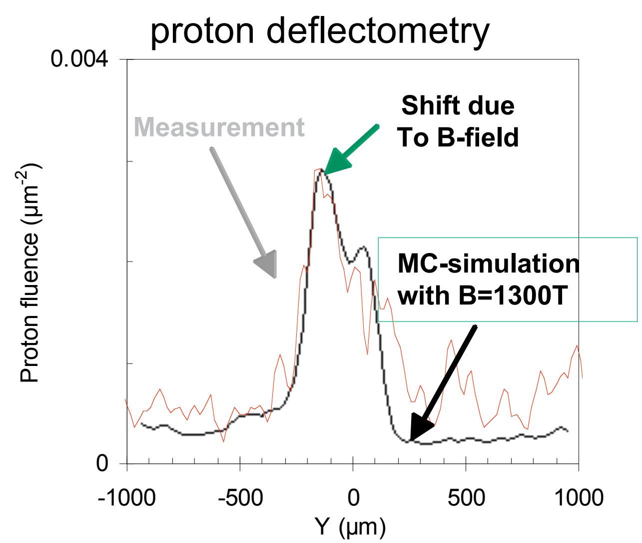




The seed field generator (MIFEDS) is operational and synchronized with the OMEGA laser







FY09 goal: Achieve compressed B-fields >2000T and temperature and fusion yield augmentation

- **Funded by OFES at ~150K/year; project includes:**
  one research associate (O. Gotchev)
  one graduate student (P. Chang, partially funded by LLE)
  one senior scientist (J. Knauer, 1 month)
  Collaboration w/MIT-HEDP group (funded by FSC)

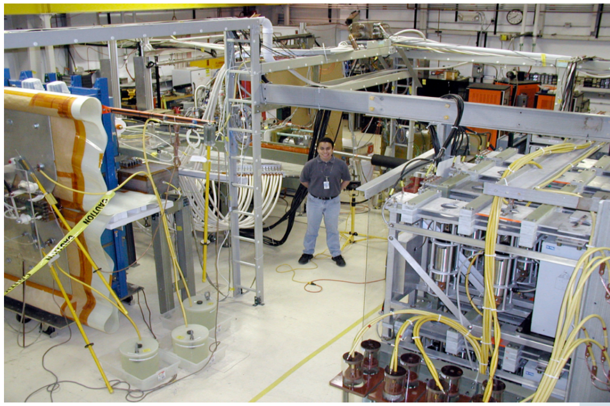
- **Three shot days on OMEGA allocated to FY08 experimental campaign; similar in FY09 (8 shots per shot-day)**

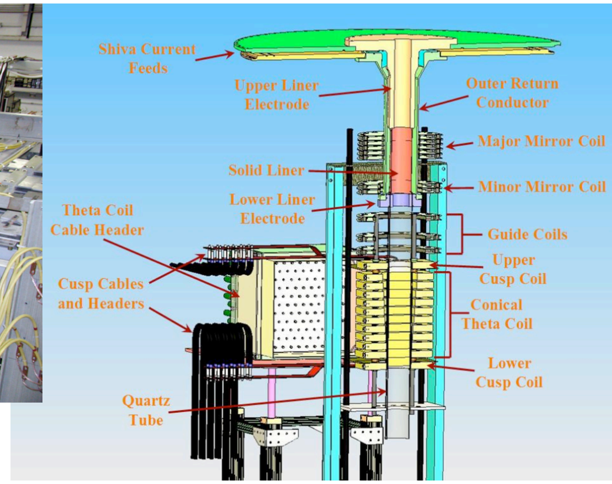
- **FY10: If magnetization of hot spot in CH targets is demonstrated, next step is magnetization of hot spot in cryogenic implosions; *requires substantial increase in funding to $0.5M/y*.**

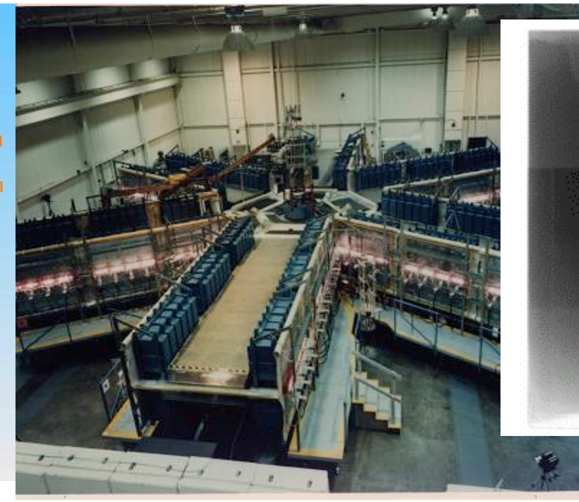
Low/intermediate gain MIF trades fusion gain for non-cryogenic targets and high-efficiency low-cost drivers

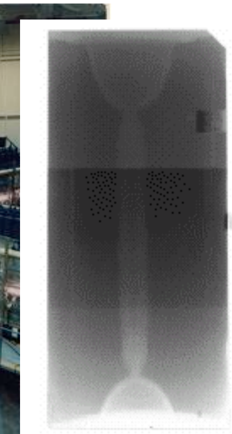
- Pulsed power has higher wall-plug efficiency and lower cost
- Lower fusion gain needed for economic power generation (for η_D~50%, G~20) $\rightarrow$ lower target density required for burn
- Gaseous/plasma initial targets could be used instead of cryogenic solid targets
- Solid, liquid, or plasma imploding liner; liner burn is a possibility

Solid liner MIF: AFRL/LANL are ready to field world's first liner-on-plasma MIF shot in FY08!





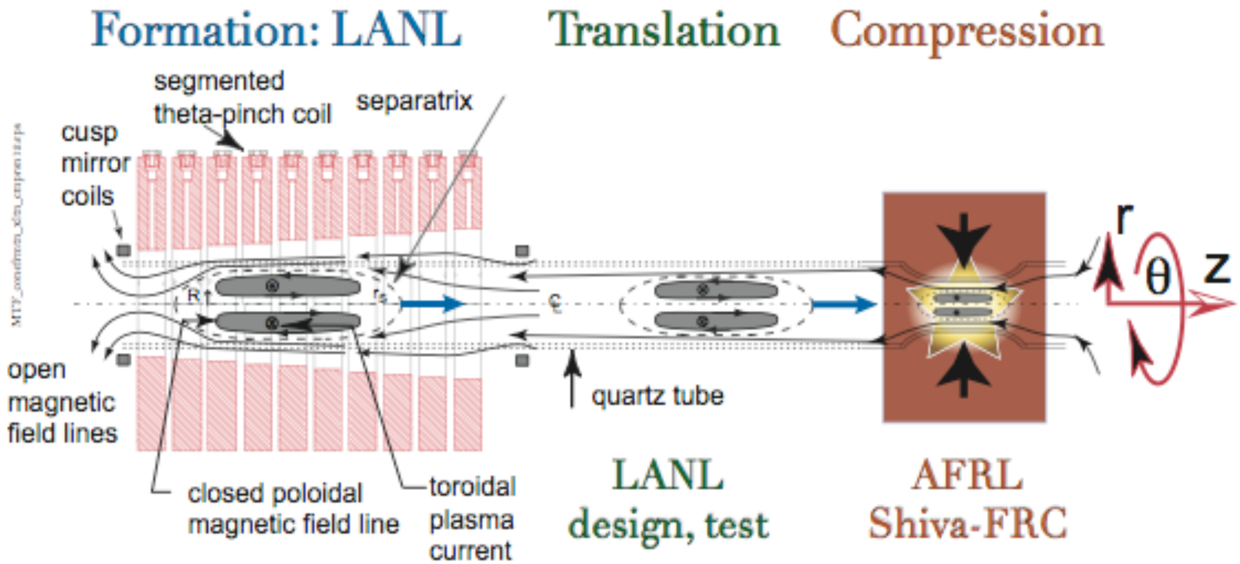




- LANL FRX-L facility demonstrated high density FRC formation ~5×10^{16} cm^3, 300 eV, ~10 μs
- Construction/assembly of FRX-L translation experiment complete
- FY08: demonstrate/optimize FRC translation/capture; FRCHX support ($1.17M)
- FY09: improve FRC lifetime/stability; FRCHX support ($1.3M)

- AFRL Shiva Star pulsed power facility: up to 9 MJ, 3 μs rise time
- Imploded a 30-cm long, 10 cm diameter, 1.1 mm thick Al liner in 24 μs reaching 0.5 cm/μs
  - 16x radial convergence
  - 1.5 MJ liner kinetic energy from 4.4 MJ stored energy
  - No observable RT instability
- *FY08: Preparations for and execution of world's first liner-on-plasma MIF implosion shots! ($1.12M)*
- FY09: MIF shot series; physics campaigns; diagnostic additions ($1.7M)

LANL/AFRL solid liner MIF scientific objectives (FY09-FY12)

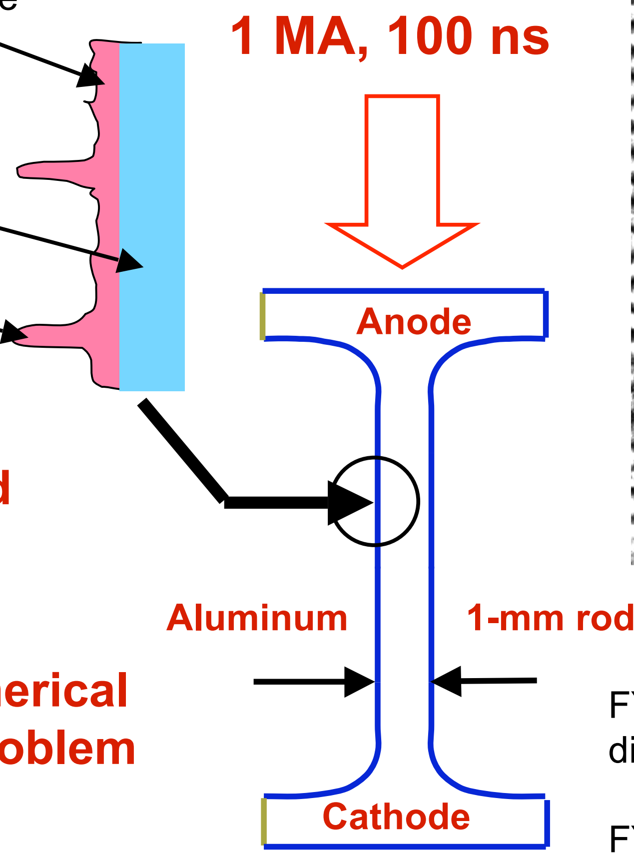


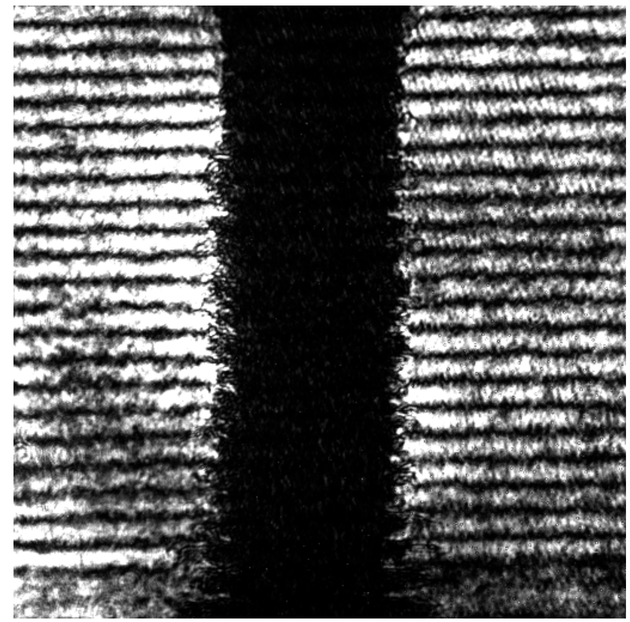
- Obtain critical scientific data on compressed magnetized target plasma; study what limits achievable T, n, τ_{dwell} (e.g., radiation losses, liner-plasma surface instabilities, FRC stability, liner geometry, etc.)
- Develop physics understanding and predictive capability for MIF fusion performance
- Full use FY10 budget (~$4M) would allow adequate staff and M&S for more shot series at AFRL enabling more effective physics campaigns; allow upgrade of LANL facility to form/study very high density MIF targets (>10^{18}cm^{-3})

HED field-matter interaction–a new MHEDLP area inspired by MIF

B.S. Bauer, R.E. Siemon, T.J. Awe, M.A. Angelova, S. Fuelling, T.S. Goodrich, V. Ivanov, I.R. Lindemuth, V. Makhin

UNIVERSITY OF NEVADA •Reno





Interferogram time of peak current B ~ 4 MG

Metal quickly ionizes and excludes flux
-- Promising for MIF

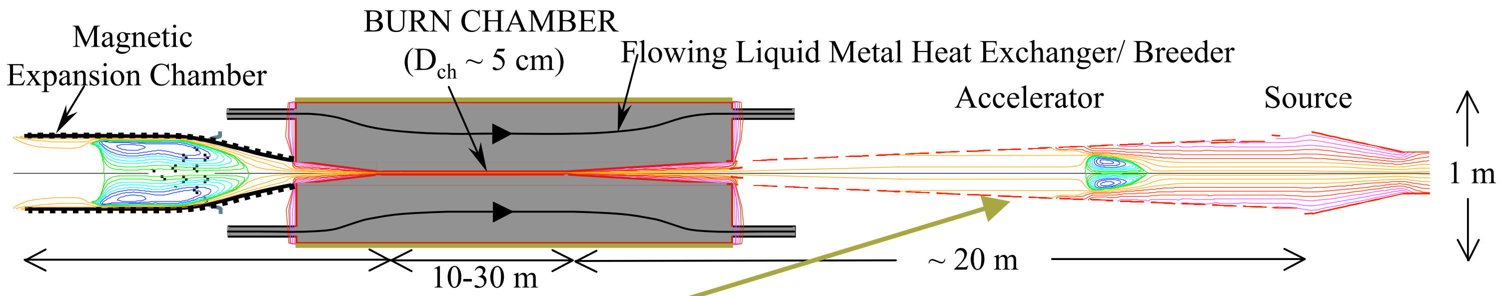
Good progress with numerical modeling but even 1D problem is complicated

FY09: continue liner studies at UNR, diagnostic support at AFRL ($280k)

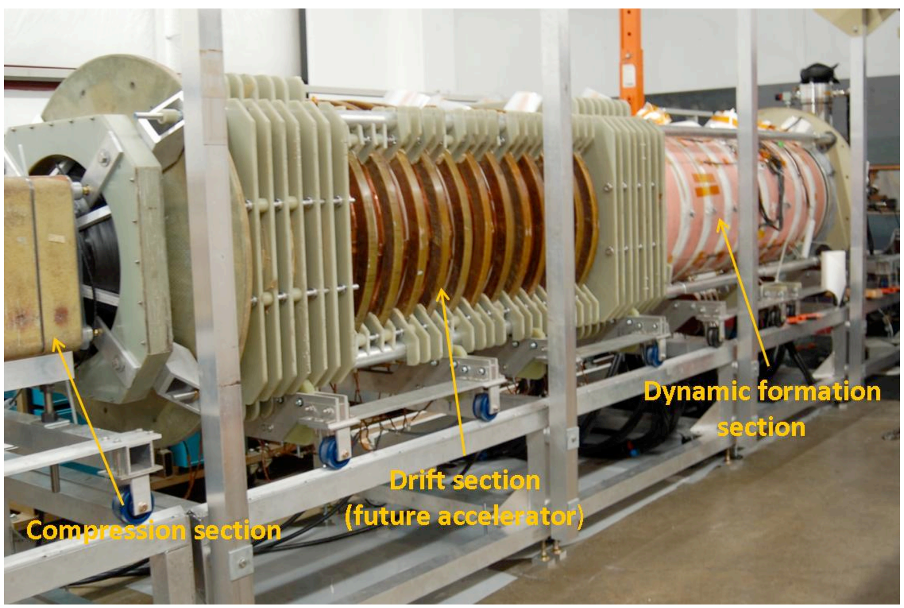
FY10: liner studies at UNR, comparisons with AFRL results

Plasma Dynamics Laboratory

Pulsed High Density (PHD) Experiment at Univ. Washington



Magneto-kinetic heating to fusion temperatures: ion energy transferred from axially sequenced low field coils



Accomplishments:

- Facility completed
- CT formation with record flux ~15 mWb
- Target initial conditions for breakeven expt. exceeded: **$n \sim 10^{21}$ m^{-3}, $T_i \sim$300-400 eV, $T_e \sim$100 eV, $V_{FRC} > 2\times10^5$ m/s**

FY08: optimize FRC formation; stability studies under acceleration/compression ($305k)

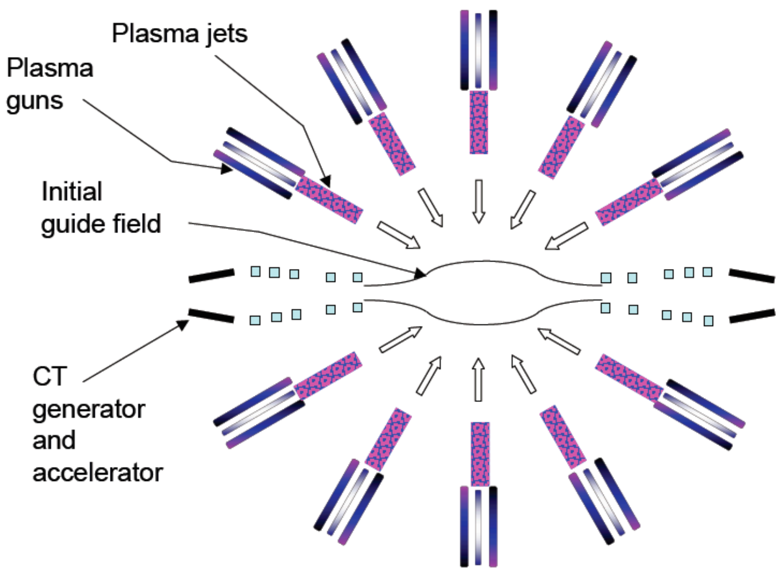
FY09: construct/install accelerator; accelerate 0.6mg FRC to 700km/s ($315k)

FY10: compress to PoP conditions (requires $1.38M to accomplish)

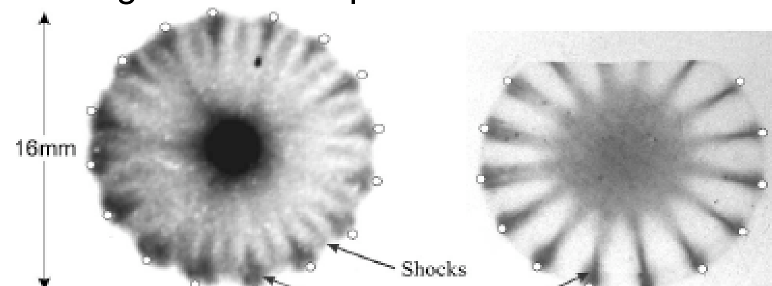
Plasma liners are being investigated as an advanced MIF driver concept

- Addresses 4 major issues for MIF
  - Standoff delivery of liner
  - Increase fusion gain
  - Repetitive operation
  - Liner fabrication and cost

Forming a plasma liner with an array of dense plasma jets:

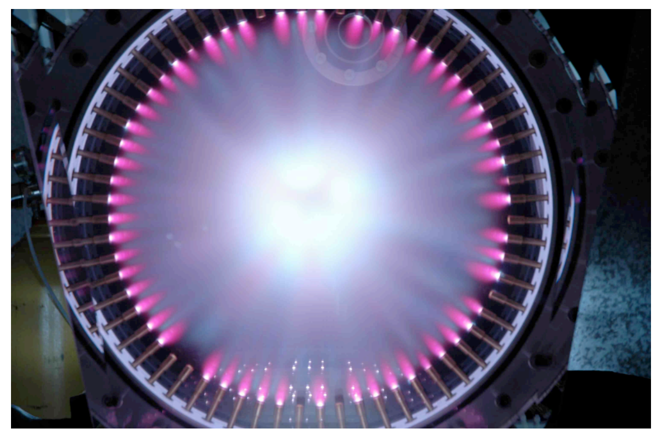


- Very high Mach-number plasma flows have been seen in wire-array Z-pinch
- Radial plasma flows stagnate on axis forming dense HED plasmas



(Bott et al., 2006)

Plasma gun development at HyperV:



Plasma jets from capillary discharges merge to form a plasma liner (Witherspoon, 2007)

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

National Plasma Jet Workshop* sponsored by OFES identifies next steps for plasma liner MIF

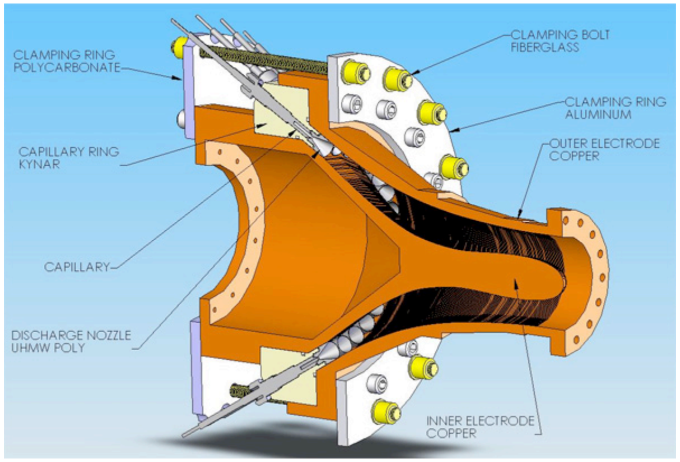
- **First U.S. Plasma Jet Workshop held at LANL Jan 24-25, 2008**
  - Attended by ~30 scientists from 7 universities, 2 national labs, and several private companies
- **Major study needed to form converging plasma liners via merging jets to reach stagnation pressures >1 Mbar, w/following objectives:**
  - Study and demonstrate required jet propagation and merging characteristics using large-scale HyperV guns
  - Form converging plasma liners in cylindrical geometry
  - Reach HED conditions (1 Mbar) with converging plasma liner
  - Develop basic suite of diagnostics
  - Enable fundamental magnetized HEDLP research
- **LANL-led multi-institutional team intends to respond w/HEDLP proposal**
- **Other needs & opportunities:**
  - Coordinated but independent MIF solid and plasma liner theory efforts
  - MFE applications of jets (refueling, disruption mitigation, rotation drive)
  - Laboratory astrophysics (e.g., jets, accretion disks)

*http://wsx.lanl.gov/Plasma-Jet-Workshop-08/workshop-talks.html

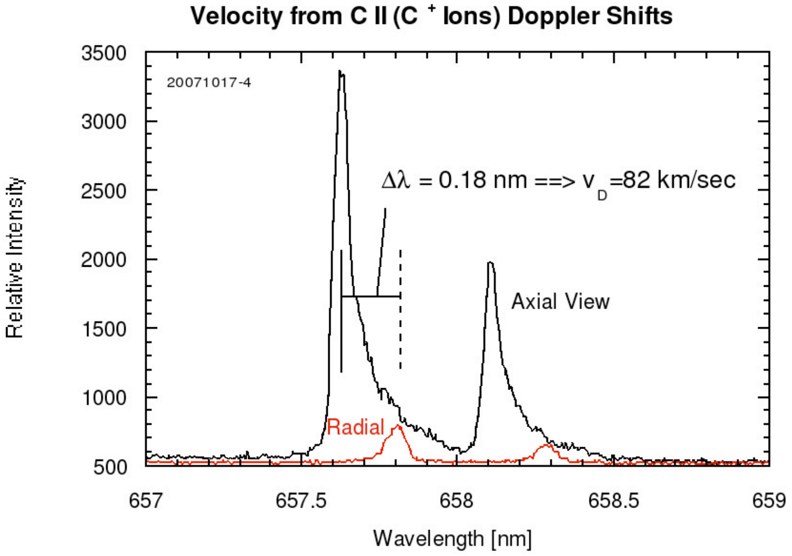
Rapid progress and breakthroughs have been made by HyperV in the past 2 years on gun development for plasma liner MIF

- **Objectives:**
  - Develop dense, high *M*, high β plasma jets ($n \sim 10^{17} cm^{-3}$, M>10, >100μg, >100km/s)
- **Applications:**
  - HEDLP studies
  - plasma liner MIF
  - MFE: disruption mitigation, refueling, rotation drive
- **Approach (based on detailed modeling):**
  - Highly collisional armature
  - High speed injection of dense pre-formed plasma
  - Electrode shape tailoring to prevent "blowby"
  - Extensive diagnostic measurements & modeling

Prototype 1 w/32 capillary injectors

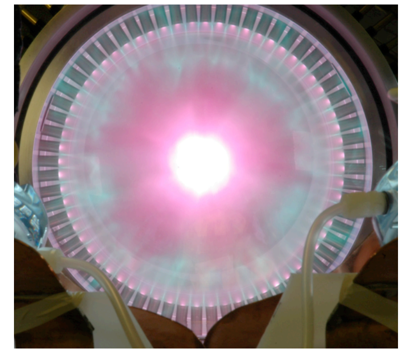


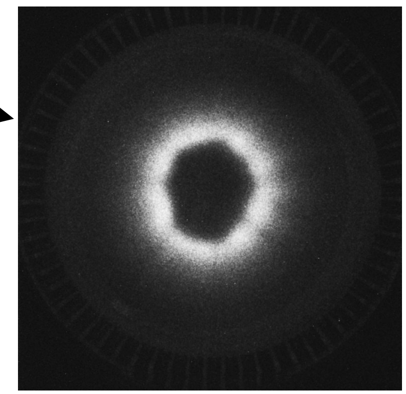
Breakthrough: first-ever demonstration of pulsed coaxial gun w/ β >>1, >150μg, >80km/s!

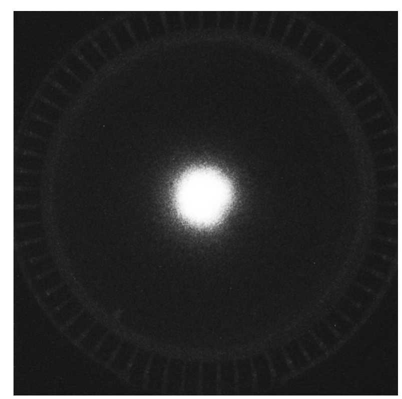


HyperV research highlights and plans

- **Highlights:**
  - Two half-scale guns built; building full-scale gun
  - Achieved jets of 160 μg at 85 km/s and ~10^{15} cm^{-3}
  - Gun installed on MCX (Maryland) for rotation drive; penetration of 2kG vacuum field achieved
  - Diagnostic suite in place
  - Prototype plasma liner formation studies
- **FY09 plan (~$562k):**
  - Extensive testing of full-scale gun to achieve jets of 100 km/s at 10^{17} cm^{-3}
  - Begin assembling hardware for full-scale merging jet experiments to be proposed by LANL
- **FY10 full use plan (~$750k):**
  - Continued gun development to higher densities & Mach number
  - Delivery of hardware and engineering support for proposed plasma liner experiment
  - Collaboration w/LANL on merging jet studies





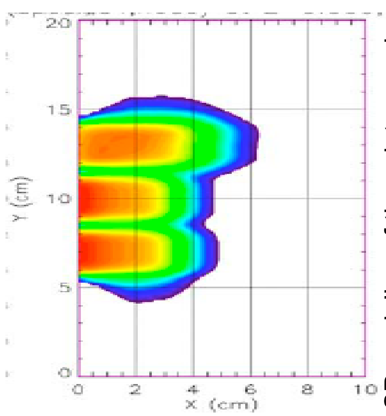


Summary of plasma liner and jet-driven MIF (PJMIF) theory/modeling efforts

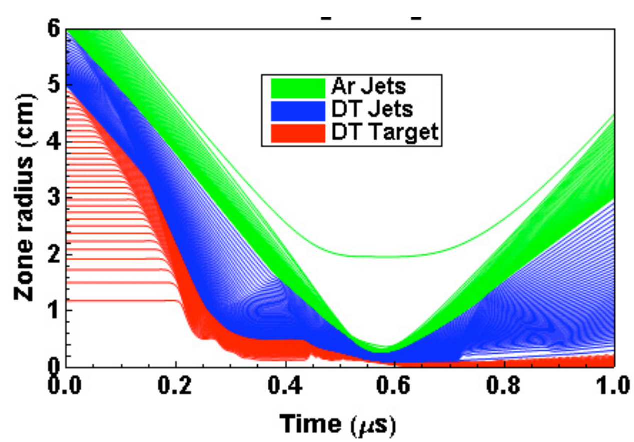
Goals: To explore “sweet spots” in PJMIF parameter space (dwell times, fusion burn/gain, α-particle transport & heat deposition, implosion dynamics, jet merging physics); code development

Institution	PI	Task	FY08 budget
HyperV*	Doug Witherspoon	Hybrid PIC code development for HEDP, MIF, fast ignition	$600k
LLNL	Dmitri Ryutov	Theory–MIF optimization	$103k
U. Wisconsin	John Santarius	BUCKY modeling of PJMIF burn dynamics	$80k
U. Alabama Huntsville	Jason Cassibry	Plasma liner, compression theory & modeling	$150k EPSCOR
Far-Tech	Jin-Soo Kim	Simulations of jet formation/merging	$375k SBIR
General Atomics	Paul Parks	Theory of plasma liners and PJMIF gain	$75k
MIT	Chiping Chen	Plasma jet & charged particle beam theory	$70k

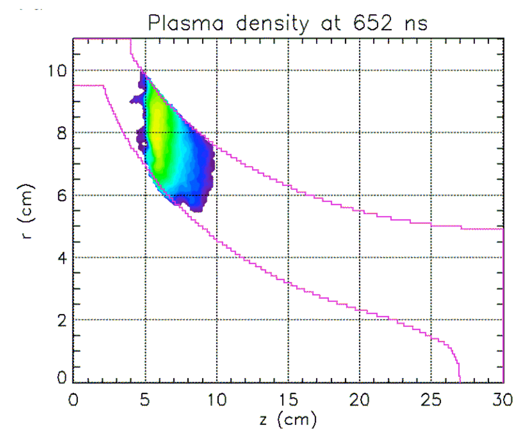
*w/Far-Tech, Prism (radiation packages), Voss Scientific (LSP PIC code)



LSP modeling of three jets merging

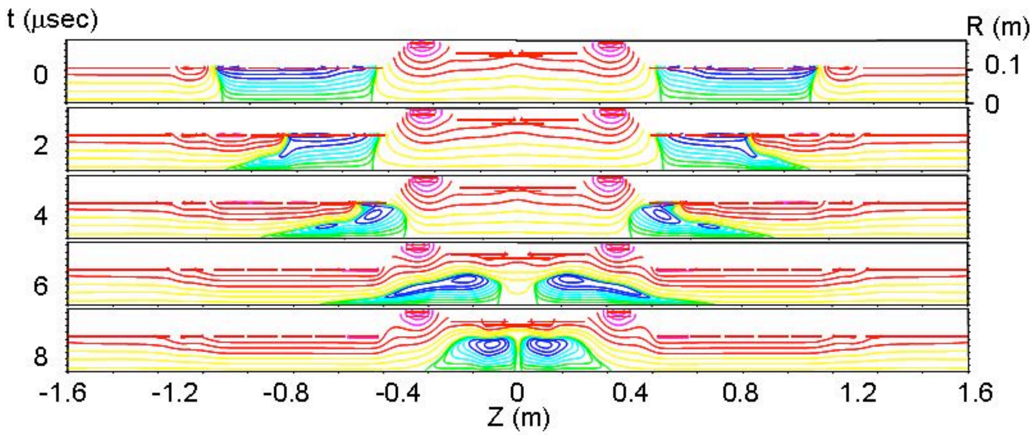


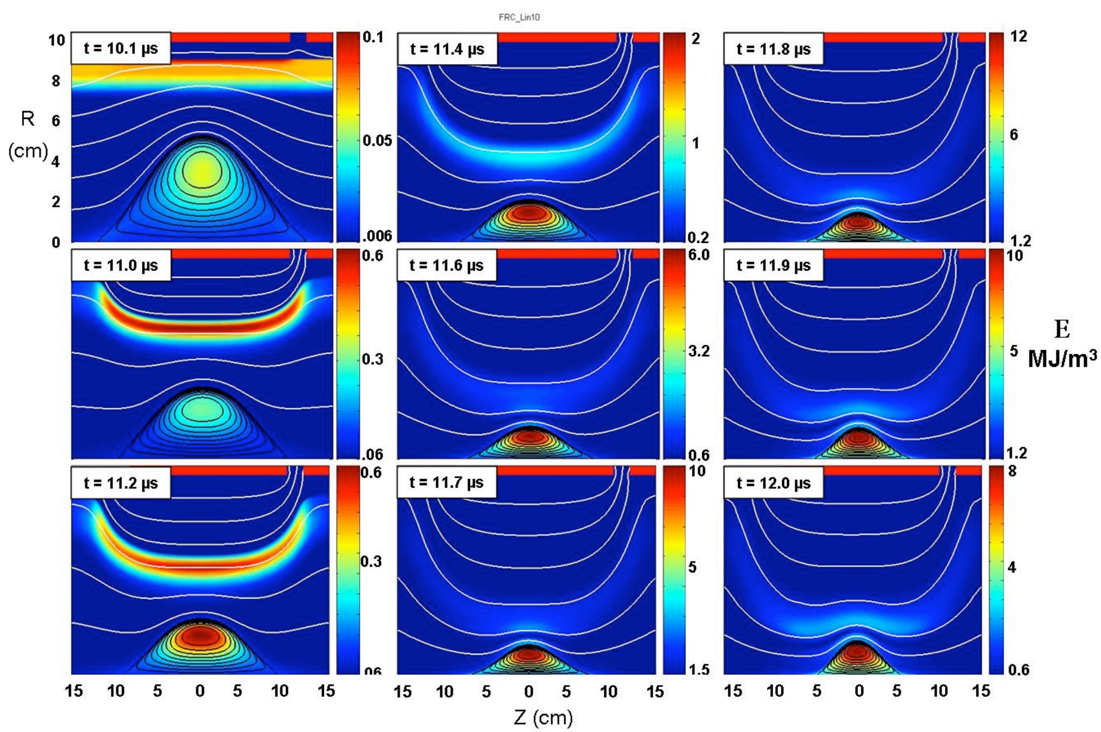
BUCKY modeling of PJMIF implosion



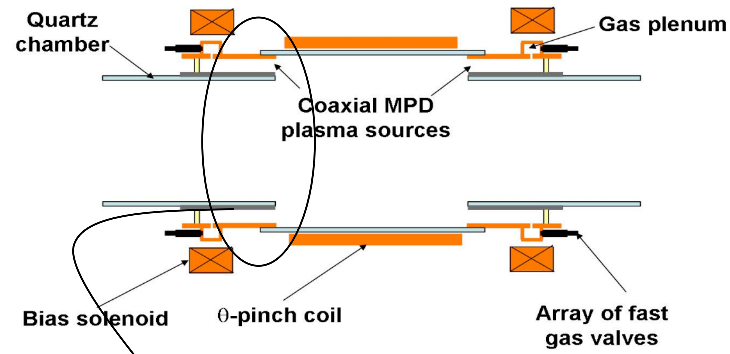
Voss modeling of gun

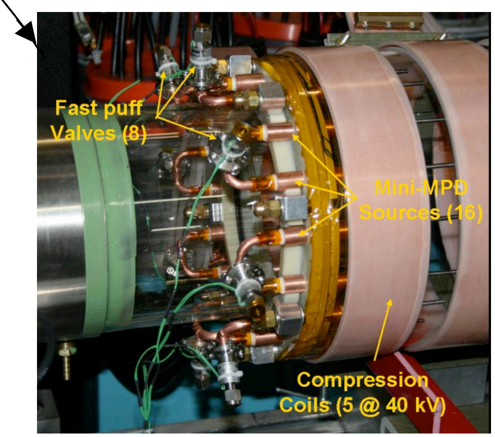
Plasma Liner Compression (MSNW, Slough)





2D MHD calculation of 1 mg plasma liner



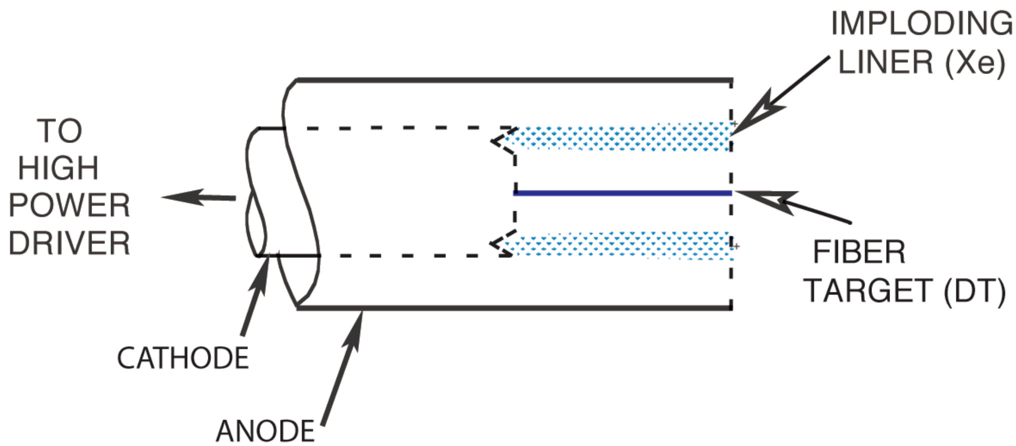


Phase I plasma liner formation experiments

FY08 ($109k + SBIR): collided FRCs w/T_i~400eV; mild compression w/B~1T resulted in ~1keV

FY09 ($109k + SBIR): plasma liner and higher B compression

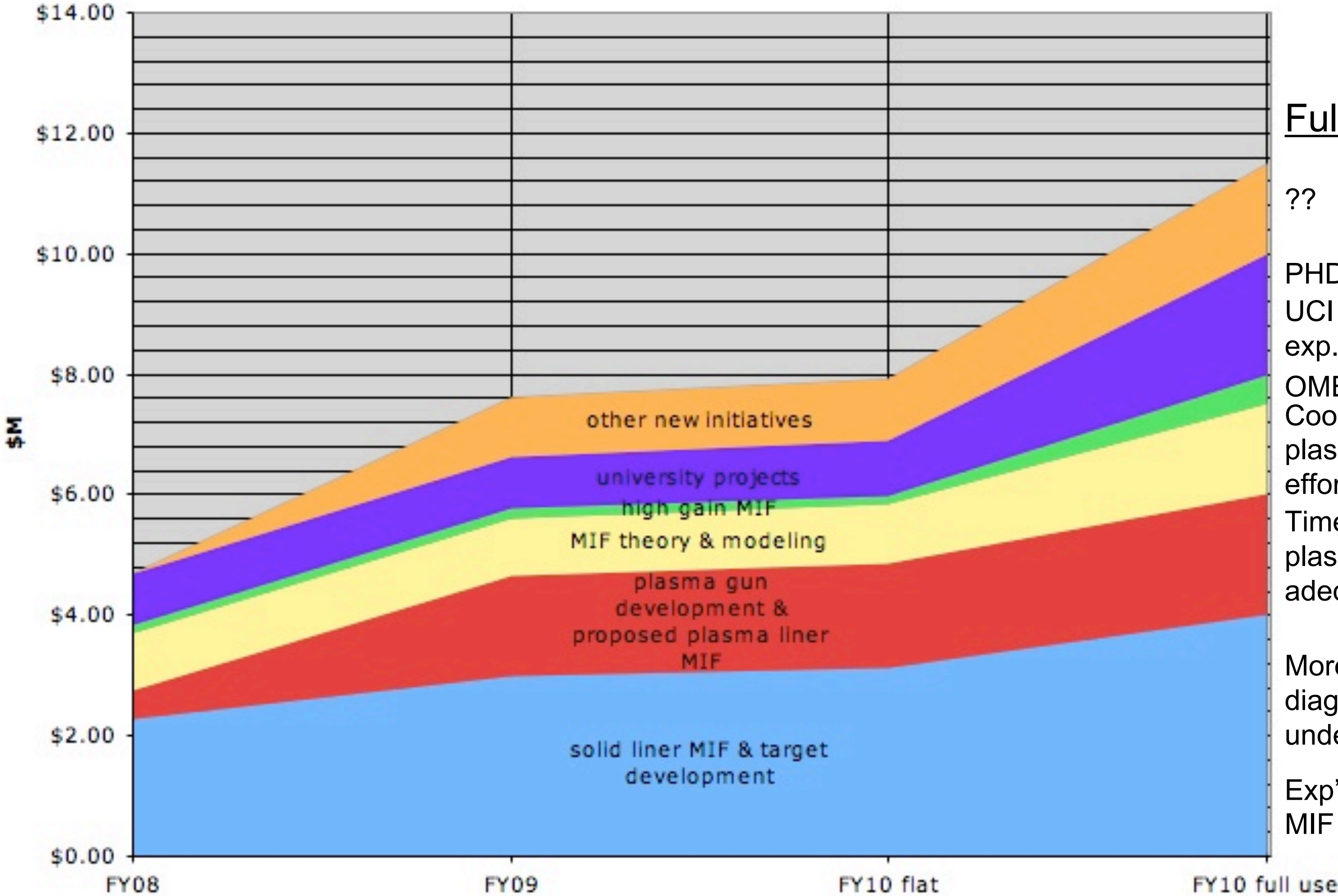
Computational studies of staged Z-pinch (UC Irvine)



FY08/09: $50k

- Mach2 (rad-MHD incl/Hall, tabulated EOS, 2.5-D, time-dependent)
- Shock heating of DT; current amplification (18→600MA) in fiber leads to high magnetic field (~600 MG); RT instability limits compression
- 100kJ capacitor bank predicted to give fusion yield of 150kJ
- FY10 full use: Experimental campaign at UNR or Sandia ($0.6M/year)

MIF program budget (FY08-FY10)



Full use enables:

??

PHD PoP exp.
UCI field Z pinch MIF exp.

OMEGA cryogenic implosion

Coordinated solid & plasma liner theory efforts

Timely path to full-scale plasma liner formation & adequate diagnosis

More MIF shot series, more diagnosis = better physics understanding

Exp's for very high density MIF targets

Summary: research over the next five years will address many critical questions for MIF

- **How can strong magnetic fields be created in an ICF hot spot, and what limits the field intensity?**

- **What limits temperature, density, and dwell time of a magnetized plasma imploded by a solid liner?**
  - *How do nearby boundaries (walls) in the presence of intense magnetic and radiation fields turn into plasmas? Will impurities transport across magnetic field?*
  - *What are the stability and transport properties of magnetized plasma during implosion?*

- **How can imploding plasma liners be formed for enabling magnetized HEDLP research and for addressing major MIF issues?**

Backup Slides

MHEDLP/MIF program profile

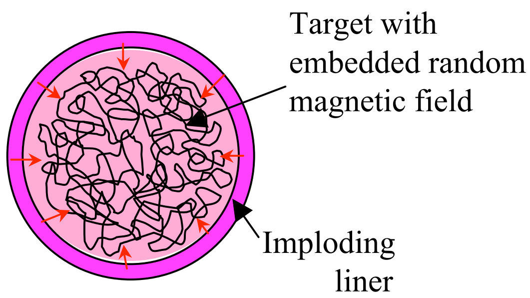
Institution	PI	Project	FY08 / FY09 $$
Univ. Rochester	Riccardo Betti	Omega MIF (compression of seed field in ICF target)	$150k / $150k
AFRL	Jim Degnan	FRCHX (solid liner MIF demonstration)	$1.1M / $1.7M
LANL	Tom Intrator	FRX-L (FRC formation & translation for MIF)	$1.17M / $1.2M
HyperV	Doug Witherspoon	Plasma gun development	$462k / $560k
LLNL, LANL, U-Wisc, UAH, GA, Far-Tech, MIT	Ryutov, Kirkpatrick, Santarius, Cassibry, Parks, Kim, Chen	Plasma liner MIF theory	$290k (+ SBIR + EPSCOR) / $300k
Univ. Nevada-Reno	Bruno Bauer	Z-pinch studies of MIF liners; AFRL collab.	$274k / $320k
Univ. Washington	John Slough	PHD (magneto-kinetic FRC compression); IPA-PLC	$413k / $423k + SBIR
UC Irvine	Frank Wessel	Staged Z pinch	$50k / $50k
HyperV (Far-Tech, VossSci, Prism)	Doug Witherspoon	Hybrid PIC development for MIF, HEDP, FI	$600k / $600k
Princeton, UNR, UNR	Fisch, Winterberg, Sentoku	MHEDP/MIF related studies	$109k / $109k
Woodruff Scientific	Simon Woodruff	Adiabatic compression of compact tori	$300k (SBIR) / $300k (SBIR)

total FY08 OFES $4.7M

THEORY RESEARCH IN MAGNETIZED TARGET FUSION (D.D. Ryutov, LLNL, $ 100K/yr)

- ***Accomplishements:***
  - Analysis of a pressurized gas as a driver for MTF, together with a local spherical blanket
  - Conceive the use of a heavy plasma liner to drive a magnetized target in a high-efficiency "soft landing"; the journal paper has been prepared for submittal
- *Project goals for FY09*
- **• Assess the possibility of increasing the fusion yield of MTF/MIF targets compared to a pure batch-burn mode by fuel injection to the hot core**
  • Consider targets with open field line geometry, including

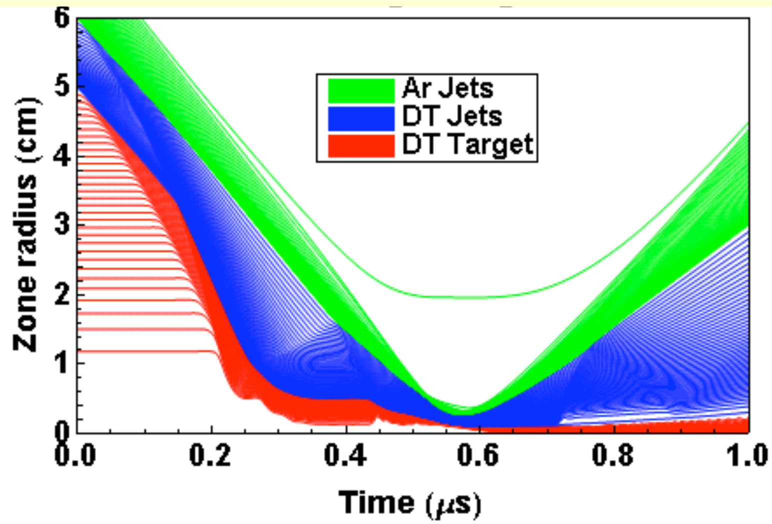
  targets with random magnetic field ("full-use": + num. simul.)
- ***Research proposals for FY10***
- **• Investigate methods for generating quasi-spherical targets inside imploding heavy plasma liner ("full-use": + num. simul.)**
- **• Consider stability of the liner-target interface including effects of the mass exchange and heat flow between the target and the liner**



Univ. of Wisconsin Modeling of Plasma-Jet Magneto-Inertial Fusion

- **Modeling MIF implosion and explosion radiation hydrodynamics using UW's 1-D BUCKY code:**
  - Lagrangian code, cylindrical or spherical geometry.
  - Equation-of-state and opacity lookup tables.
  - Full burn dynamics, including fusion α's.

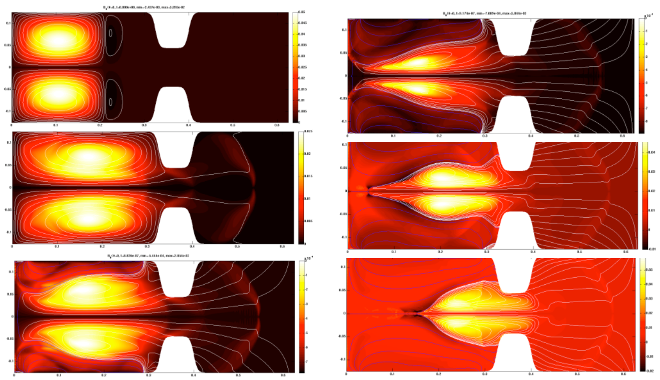
Lagrangian (constant mass) zone evolution



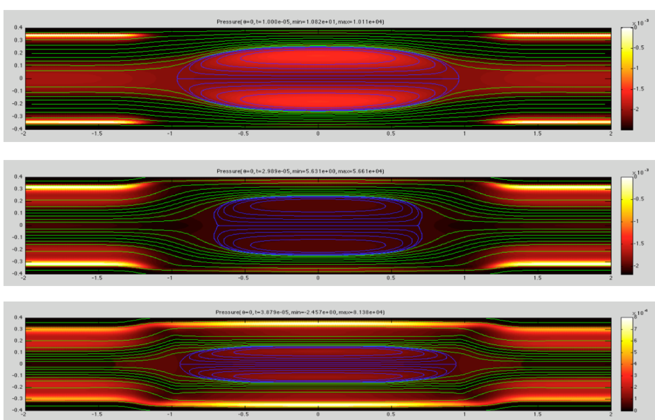
- **FY08-10 plan ($80 K/yr):**
  - Refine B-field model for individual zones.
  - Refine α-particle deposition model.
  - Include higher-mass liner ions with realistic equations-of-state, partial ionization states, and high jet Mach numbers.
  - Study target-liner boundary layer effects.
  - Model MIF and plasma-jet experiments.
  - Investigate potential MIF experiments.
  - Optimize MIF conceptual designs for maximum Q.

WOODRUFF SCIENTIFIC,LLC

Analytic and Computational Modeling of the Adiabatic Compression of Compact Tori

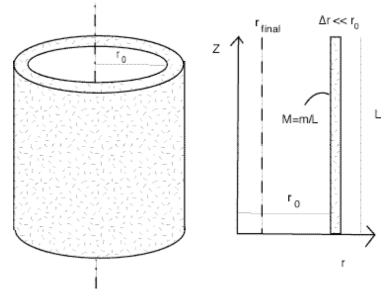


SPHEROMAK



FRC

WS aims to address critical physics issues relating to the production of magnetized HED lab plasmas by use of state of the art computational codes and analytic modeling.



$$1/2\,Mv^2 = W_{\mathbf{B}}$$

$$\pi r_1 d\rho_L v^2 = \frac{B^2}{2\mu_0}\frac{dV}{L} = \frac{B^2}{2\mu_0}\pi r_1^2$$

$$\rightarrow B_{\max} = \sqrt{\frac{d\rho_L}{2 r_1 \mu_0}}\,v$$

$$1/2\,Mv^2 = W_{nkT}$$

$$\rightarrow T_{\max} = \frac{d\rho_L}{r_1 n k} v^2$$

Recent Accomplishments:

- Simulations of FRC and Spheromak compressions.
- Coil geometries analyzed computationally and analytically.
- Simulation and analytic theory capability developed, NERSC time allocated.

Present Work:

- Assessing merits of Liner compression vs coil compression.
- First results to be reported at ICC workshop.

Work at WS is supported by DOE SBIR contracts DE-FG02-07ER84924 and DE-FG02-06ER84449

WOODRUFF SCIENTIFIC,LLC

Budget and schedule (FY09), research plans.

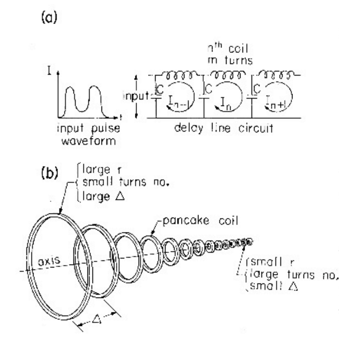
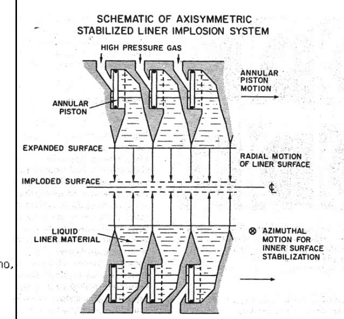
Baseline budget would be 300k.

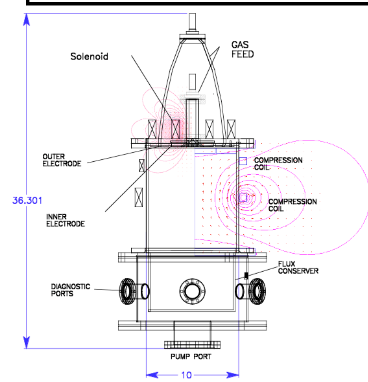
FY09 tasks:

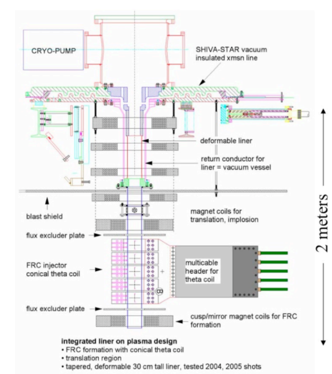
- 3D MHD simulations with realistic geometry and boundary conditions for existing experiments.
- Expand capabilities for shock capturing.
- Compare with analytical scaling.
- Compare with experimental results.

+20% increment would allow atomic physics to be addressed.

-10% would mean not implementing experiment-like diagnostics in the model.

Traveling wave coil compression	**Liners**
	
Pro: fast, simple, clean	*Pro:* proven
Con: stability of target plasma? Cost of bank?	*Con:* Messy (liquid lead!), slow compression (need target with long life)





PBX @ WS, LLC MTF @ LANL

Work at WS is supported by DOE SBIR contracts DE-FG02-07ER84924 and DE-FG02-06ER84449

Voss Scientific Budget,* Plans for FY08-FY10

- Projected Budget for FY08 – $150k
  - **Complete installation of plasma sheath model, 2D radiation transport and EOS for plasma jet simulation**
  - **Benchmark simulation against HyperV jet data**
  - **Begin optimization of new numerical solution technique for fast implicit and EMHD solution**
- Projected Budget for FY09 – $140k
  - **Complete optimization of 2 level domain decomposition scheme for LSP with matrix inversion technique for advanced jet design. Determine most efficient solver.**
  - **Determine best EMHD solution technique for robust and fast but approximate jet simulation.**
  - **Implement 3D radiation transport and SPECT3D interface.**
- Plans for FY10 and beyond– $146k per year
  - **Implement accurate fusion product transport model for Magneto-Inertial Target Fusion**
  - **Benchmark new fully-integrated physics packages against HyperV jet accelerator data**

*Sub-contracted through HyperV PIC code grant.